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ARMY RESEARCH LABORATORY

Hit Probability of a High Velocity Tank Round

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ARL-MR-49 March 1993

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
March 1993

3. REPORT TYPE AND DATES COVERED
Final, Jan 90-Sep 92

4. TITLE AND SUBTITLE
Hit Probability of a High Velocity Tank Round

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
Fred Bunn

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WT-WE
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-OP-CI-B (Tech Lib)
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-MR-49

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report, in support of the Ballistics for Future Systems program, analyzes the improvement in tank cannon hit probability to be gained by increasing the muzzle velocity. It finds negligible improvement in hit probability against a stationary target but significant improvement in hit probability against a moving target. It also compares the effect of improving the fire control with increasing the muzzle velocity. Doubling the muzzle velocity appears superior to a first order predictor but inferior to a second order predictor.

14. SUBJECT TERMS
hit probabilities, accuracy, tank armor, high velocity

15. NUMBER OF PAGES
27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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ACKNOWLEDGEMENTS

Fred Bunn, Geoffrey Sauerborn, and Joe Olah performed this study. Dr Judy Temperley, John Groff, Toney Perkins, and William D'Amico of the Army Research Laboratory provided advice and suggestions. Fred Brandon, and Francis Mirabelle of the ARL provided data. Richard Norman of the Army Systems Analysis Agency provided data and the PH1 computer for producing accuracy data against a stationary target. John Groff's group provided data and computer programs for calculating accuracy data against moving targets.

The study team wishes to express their appreciation for the generous support we have received.

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1. INTRODUCTION

Given a modern tank, how will performance be affected by increasing the muzzle velocity? More specifically, how does increasing muzzle velocity affect the hit probability of a stationary firer shooting at a stationary or moving target? Since current fins would burn off the round if it is fired at a significantly higher muzzle velocity, how does the hit probability of a cone-tailed round compare with that of a finned round? What is the tradeoff between fire control sophistication and muzzle velocity?

The study reported here is based on computer calculations which are in turn based on the laws of physics, ballistics, and data available from prior field tests.

This report discusses how we arrived at the following conclusions:

1. Doubling the speed of a KE round yields almost no improvement in hit probability against a stationary target.
2. Doubling the speed of a HEAT round yields a 13 percent increase in hit probability against a stationary target at three kilometers and a 30 percent increase in hit probability against a stationary target at four kilimeters. These are relative increases. The absolute increases are small at these long ranges.
3. Doubling the speed of a KE round yields a 30-35 percent increase in hit probability against moving targets at one kilometer and a 55-60 percent increase in hit probability at two kilometers. The relative increase is even larger for moving targets at three and four kilometers but the absolute increase is quite small.
4. Doubling the speed of a HEAT round yields a similar pattern of increases in hit probability against moving targets.
5. Replacing the current fire control with an improved fire control using a first order predictor yields the same increase in hit probability as doubling the speed of the round if the moving target is at one kilometer. If the moving target is at longer ranges, doubling the speed of the round is more effective than improving to a first order predictor. Combining both improvements appears to be additive; we see no synergism.
6. Replacing the current fire control with an improved fire control using a second order predictor yields a greater increase in hit probability than doubling the muzzle velocity for targets out to three kilometers range. Beyond that, either improvement yields approximately equal benefits. Again, combining the improvements appears to be additive rather than synergistic.

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2. HIT PROBABILITY ON A STATIONARY TARGET

We varied muzzle velocity of a conventional, finned KE round from 1600 m/s to 3000 m/s to find the hit probability. Since these fins tend to burn off, we also found hit probabilities for KE rounds that use a four degree flared tail and a 15 degree flared tail for stabilization.

The four degree flared round has a five percent smaller dispersion and the 15 degree flared round has a 15 percent smaller dispersion. Unfortunately, the flared tail rounds have a higher drag, increasing their times of flight. The increased time of flight causes an increase in the horizontal and vertical variable bias errors. The horizontal components that increase are cant and crosswind. The vertical components that increase are muzzle velocity variation, range estimation, range wind, air temperature, air density, and vertical cant. The major contributors are crosswind horizontally and muzzle velocity variation vertically. Often, these more than offset improvements in dispersion. For this reason, when rounds are launched at the lower velocities, the flared tail rounds will hit a little less often than a finned round.

Figure 1 shows four sets of four curves. Each curve shows how increasing muzzle velocity increases hit probability. The uppermost set of curves is for a target at one kilometer. The second set is for a target at two kilometers. The third set is for a target at three kilometers, and the lowest set is for a target at four kilometers. Within each set, the solid curve is a standard finned KE round, the dashed curve is for a four degree flared tail round, the dotted curve is for a 15 degree flared tail round, and the broken curve is for a HEAT round.

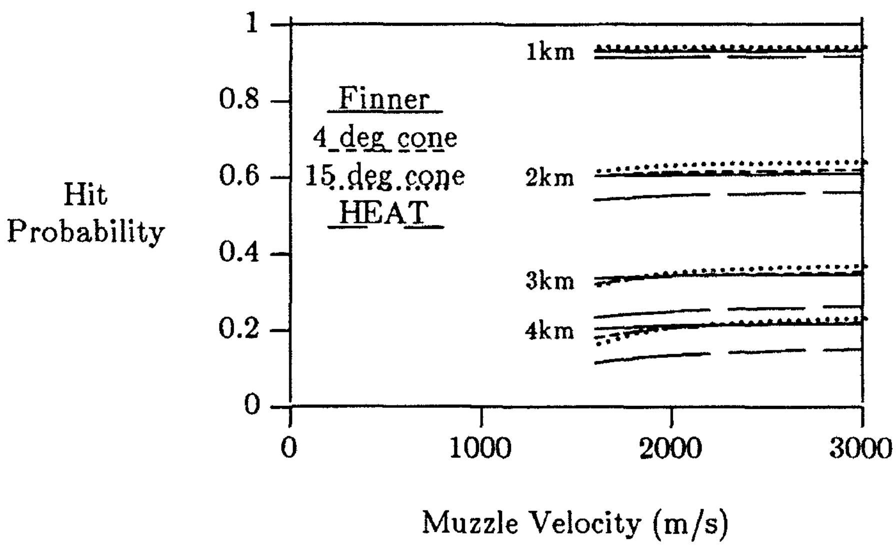

Figure 1. Hit Probability on a Stationary Target

The higher velocity portions of the solid curves assume the fins will not burn off. In actuality, they will. We don't know at what velocity this will occur, but it can be increased by improving the heat resistance of the fins. This is being worked on.

These curves show that, in general, increasing the muzzle velocity will not increase the hit probability against a stationary target. This is true except for the cone tail rounds fired at the longer range targets with a muzzle velocity between 1600 m/s and 1900 m/s. Why? Because the rounds with the cone tails have a higher drag and tend to "run out of steam" at three kilometers.

3. TARGET MOTION

Next, we generated hit probabilities against a moving target on three paths. These paths are the standard paths used in Materiel Need documents and are known as the STAGS, ATMT, and TEMAWS paths. Figure 2 shows the lateral motion of the target on each path as time passes.

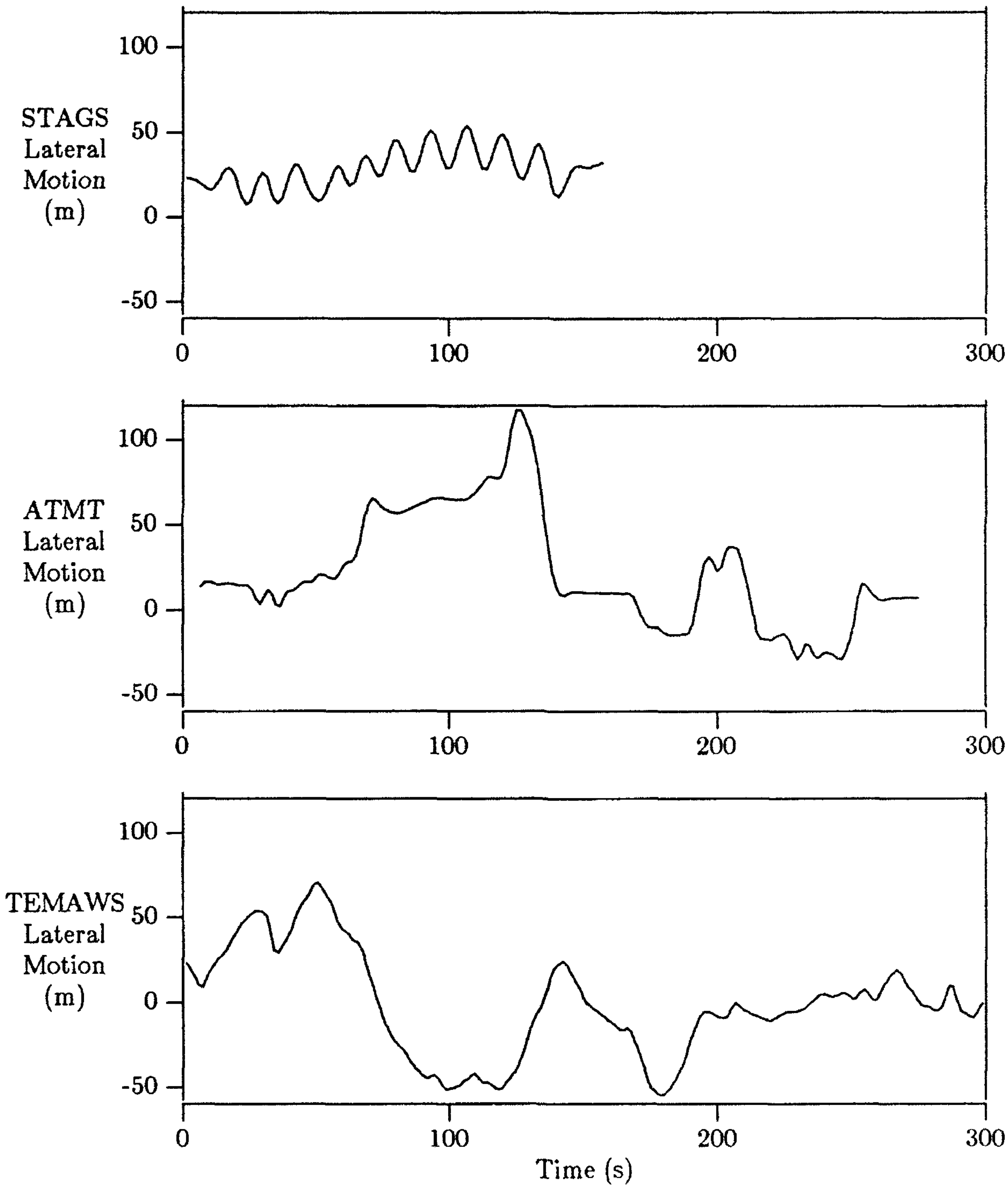

Figure 2. Target Paths

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4. HIT PROBABILITY ON MOVING TARGETS

Figure 3 shows that increasing muzzle velocity increases the hit probability against the STAGS target. At one kilometer, the increase is about 30 percent and at four kilometers, the increase is perhaps 50 percent, but from a very low base.

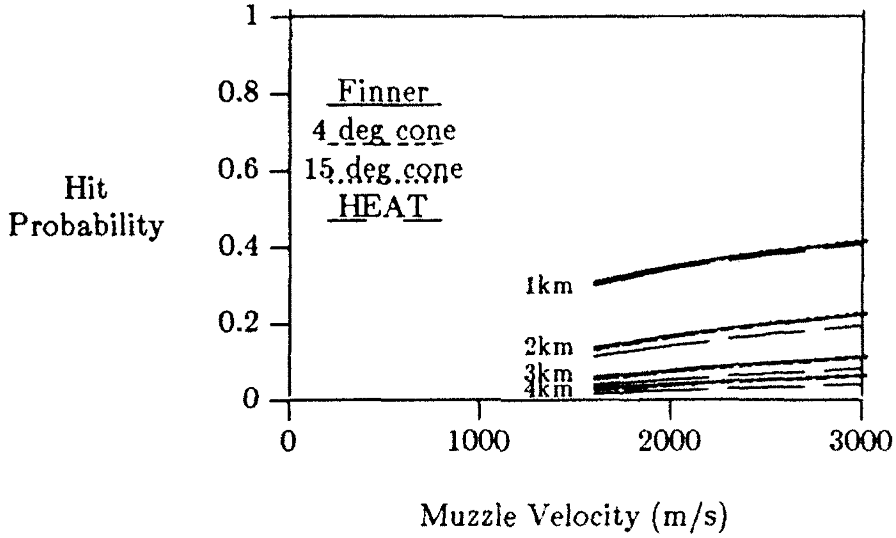

Figure 3. Hit Probability on STAGS Target

Figure 4 shows the performance against the ATMT target. Since it is easier to track, the hit probabilities are a little higher.

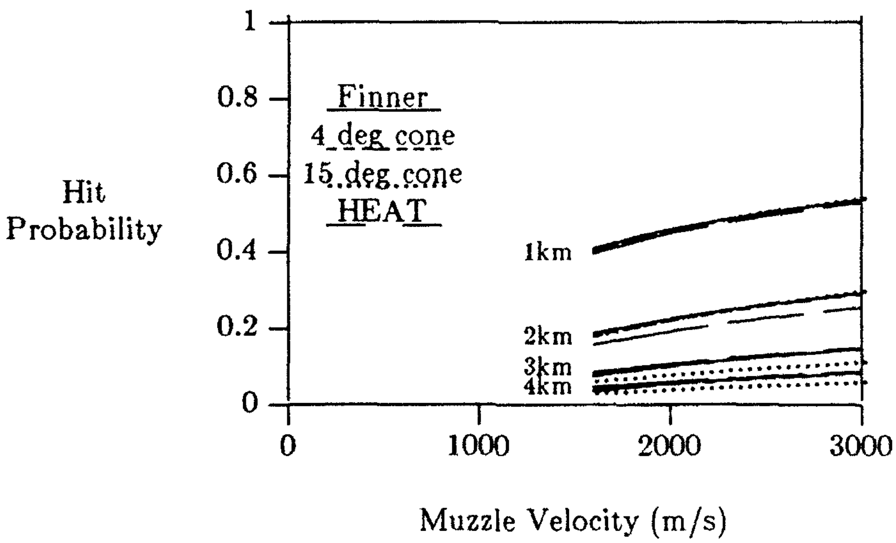

Figure 4. Hit Probability on ATMT Target

Figure 5 shows the performance against the easiest maneuvering target, the TEMAWS target.

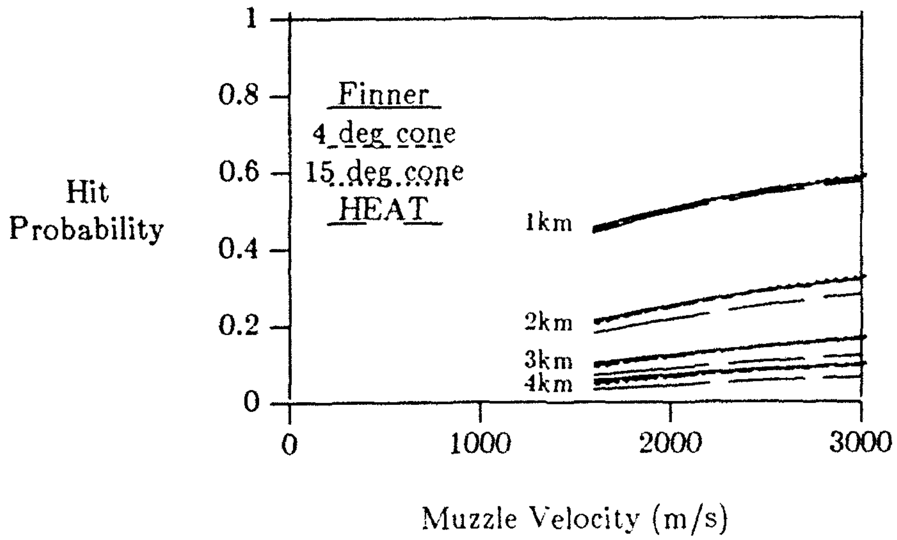

Figure 5. Hit Probability on TEMAWS Target

4.1 First Order Gun Directors

We next look at an improved fire control. Figure 6 shows that increasing muzzle velocity increases the hit probability against the STAGS target. At one kilometer, the increase is about 30 percent and at four kilometers, the increase is perhaps 50 percent, but from a very low base.

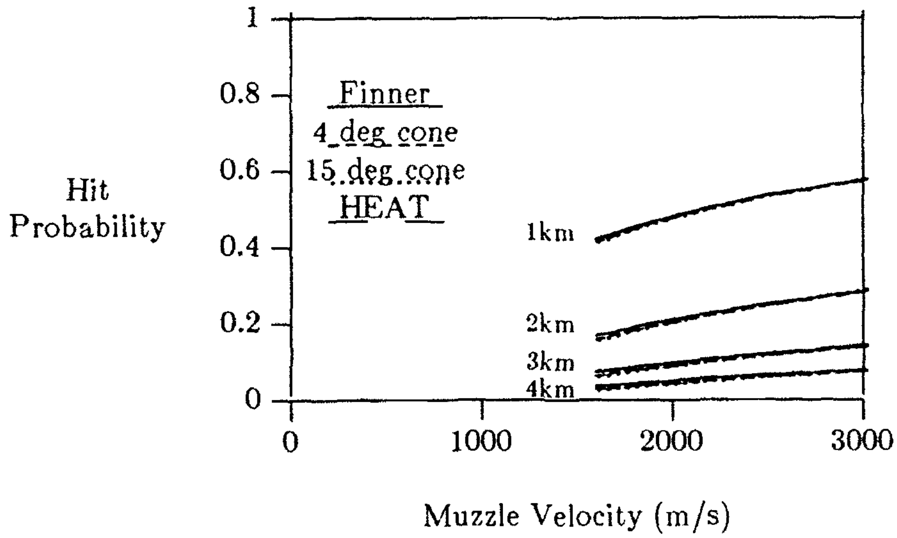

Figure 6. Hit Probability on STAGS Target

Figure 7 shows the performance against the ATMT target. Since it is easier to track, the hit probabilities are a little higher.

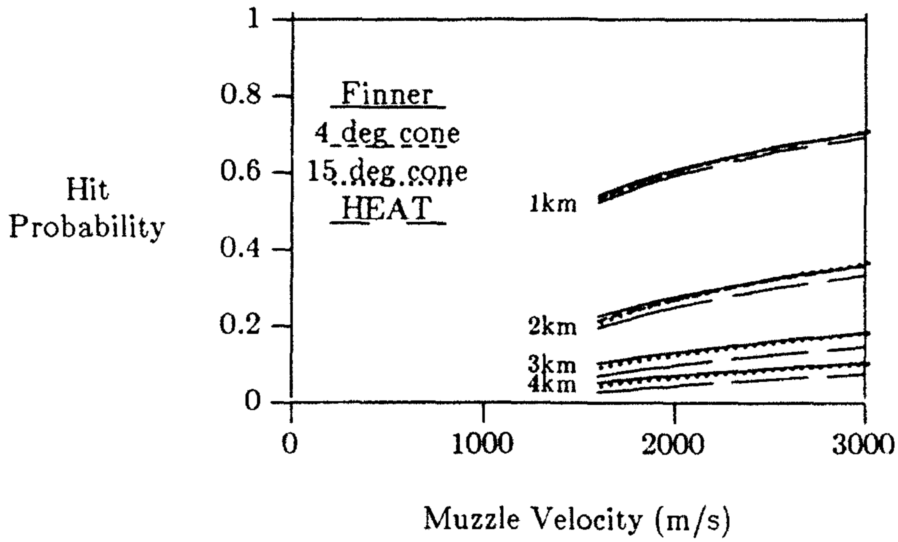

Figure 7. Hit Probability on ATMT Target

Figure 8 shows the performance against the easiest maneuvering target, the TEMAWS target.

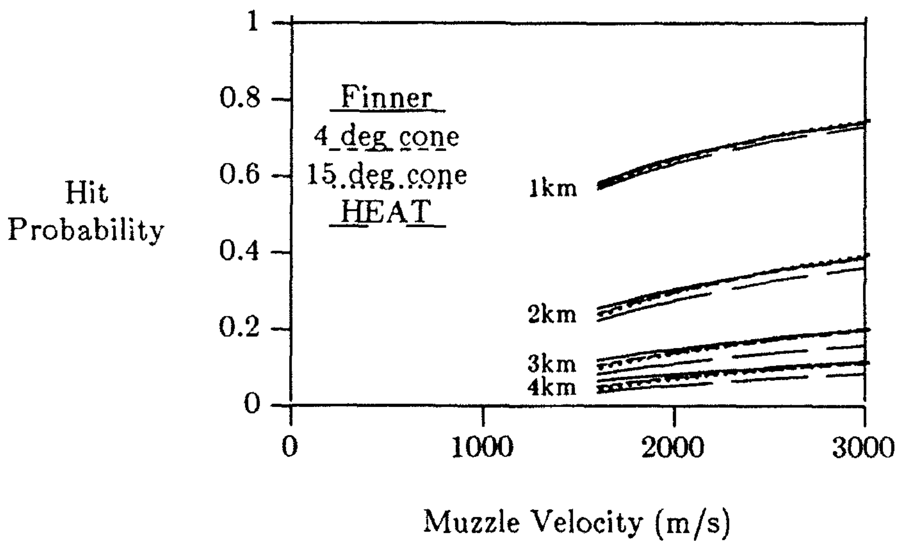

Figure 8. Hit Probability on TEMAWS Target

4.2 Second Order Gun Directors

Figure 9 shows that increasing muzzle velocity increases the hit probability against the STAGS target. At one kilometer, the increase is about 30 percent and at four kilometers, the increase is perhaps 50 percent, but from a very low base.

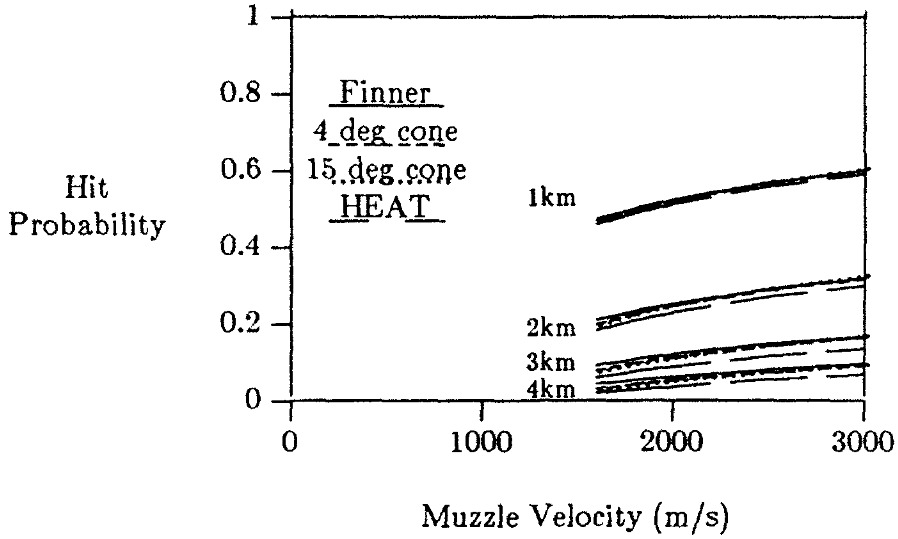

Figure 9. Hit Probability on STAGS Target

Figure 10 shows the performance against the ATMT target. Since it is easier to track, the hit probabilities are a little higher.

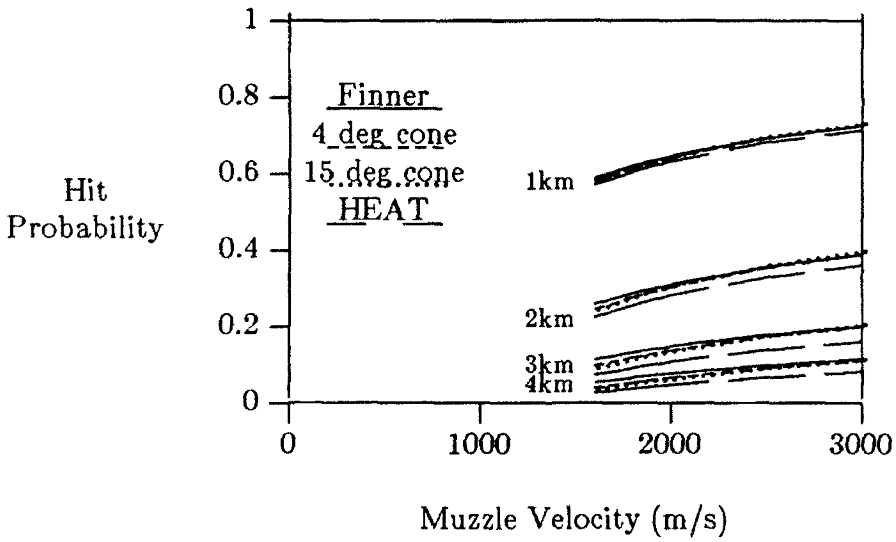

Figure 10. Hit Probability on ATMT Target

Figure 11 shows the performance against the easiest maneuvering target, the TEMAWS target.

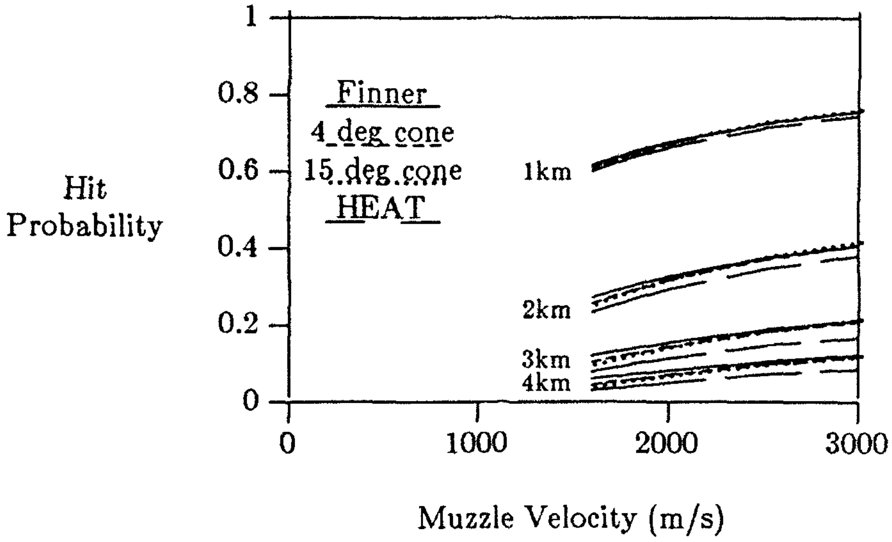

Figure 11. Hit Probability on TEMAWS Target

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5. COMPARISON OF METHODS TO IMPROVE HIT PROBABILITY

We have found the baseline hit probabilities and the hit probabilities when we make these improvements: a) increase muzzle velocity, b) use an improved fire control with a first order predictor, c) use an improved fire control with a second order predictor. The question now is, which of these improvements is most effective? Is doubling the muzzle velocity more or less effective than substituting an improved fire control with a first order predictor? Is doubling the muzzle velocity more or less effective than substituting an improved fire control with a second order predictor?

Here we will compare the improvements using the fin stabilized round fired at a target on the STAGS path. The conclusions drawn will be applicable to the other rounds and paths.

Figure 12 shows the hit probability as a function of range for the baseline finner at 1600 m/s, a high velocity version at 3000 m/s, a first order predictor, and the combination of the two improvements. For a target at one kilometer, either improvement yields equal benefits. Beyond one kilometer, doubling the muzzle velocity yields a bigger payoff.

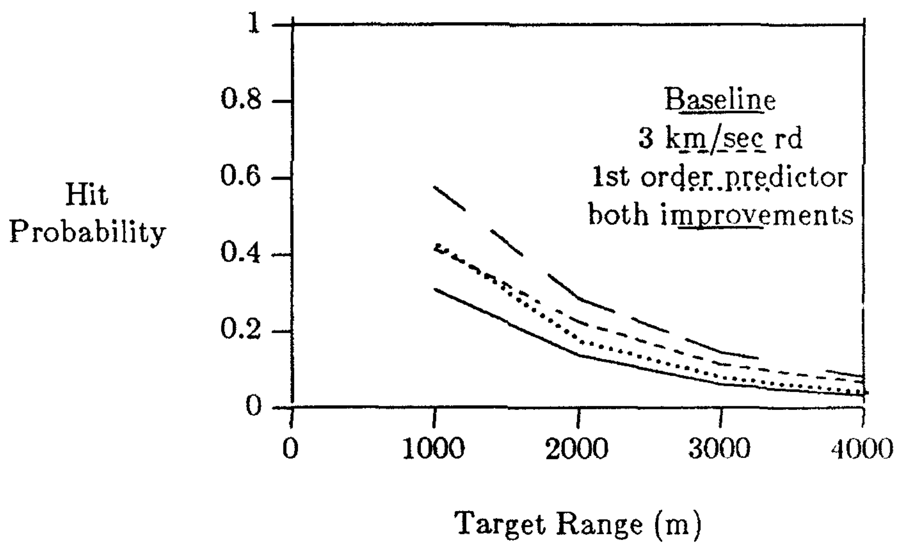

Figure 12. Doubling Speed vs Substituting First Order Fire Control

Figure 13 shows the hit probability as a function of range for the baseline finner at 1600 m/s, a high velocity version at 3000 m/s, a second order predictor, and the combination of the improvements. For target ranges less than three kilometers, improving to a second order fire control yields a greater payoff than doubling the muzzle velocity. From three kilometers on out, either method yields the same increase in hit probability.

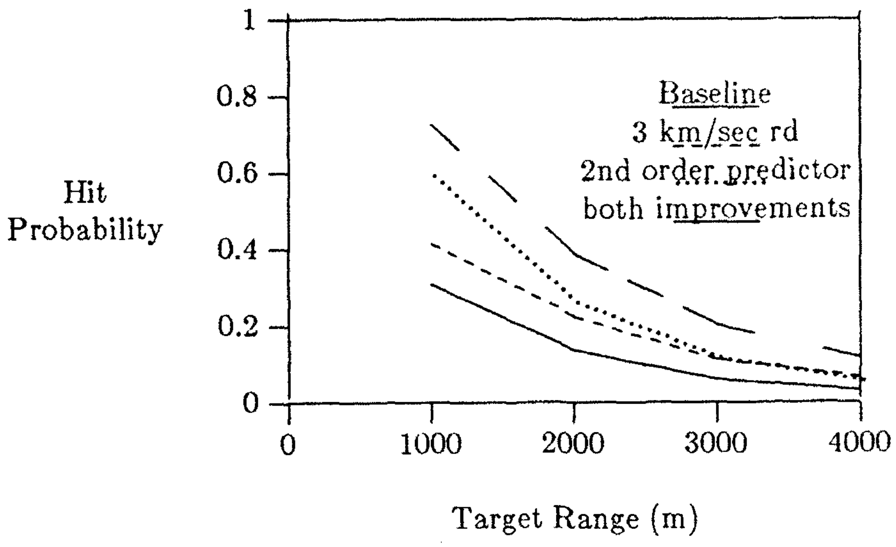

Figure 13. Doubling Speed vs Substituting Second Order Fire Control

6. SUMMARY

We draw the following conclusions:

1. Doubling the speed of a KE round yields almost no improvement in hit probability against a stationary target.
2. Doubling the speed of a HEAT round yields a 13 percent increase in hit probability against a stationary target at three kilometers and a 30 percent increase in hit probability against a stationary target at four kilimeters. These are relative increases. The absolute increases are small at these long ranges.
3. Doubling the speed of a KE round yields a 30-35 percent increase in hit probability against moving targets at one kilometer and a 55-60 percent increase in hit probability at two kilometers. The relative increase is even larger for moving targets at three and four kilometers but the absolute increase is quite small.
4. Doubling the speed of a HEAT round yields a similar pattern of increases in hit probability against moving targets.
5. Replacing the current fire control with an improved fire control using a first order predictor yields the same increase in hit probability as doubling the speed of the round if the moving target is at one kilometer. If the moving target is at longer ranges, doubling the speed of the round is more effective than improving to a first order predictor. Combining both improvements appears to be additive; we see no synergism.
6. Replacing the current fire control with an improved fire control using a second order predictor yields a greater increase in hit probability than doubling the muzzle velocity for targets out to three kilometers range. Beyond that, either improvement yields approximately equal benefits. Again, combining the improvements appears to be additive rather than synergistic.

Future plans are to integrate the probability of kill given a hit with the probability of hit data generated for this report. At that time, we will generate curves of the single shot kill probability as a function of muzzle velocity. We expect them to show a steeper slope, implying a greater increase in effectiveness.

We then plan to simulate combat in the Tank Wars[1] model and find win probabilities for the rounds at these increased muzzle velocities. We hazard no guess as to the slope of the performance curves that will be generated.

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1. Bunn, Fred L. *The Sustained Combat Model: Tank Wars II Programmers' Manual*, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 21005, BRL-TR-3292, November 1991.

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Appendix A. Methodology

To generate hit probabilities for the stationary firer versus the stationary target, we obtained and modified the AMSAA Phl[2] program. The modifications allowed us to:

1. Run on the smoke computer,
2. Use Fortran 77,
3. Generate accuracy data with lay error removed for runs with a moving target, and
4. Generate fire control constants for moving target runs.

To exercise the Phl program, we constructed a shell file, xss, that would execute the program 20 times, once for each of four ranges at five muzzle velocities. Before executing the program it would modify the basic input file and after executing, it would catenate summary results and plot hit probability curves. This saved many hours of manual intervention and avoided errors in the data preparation and analysis process.

We then constructed a shell file, mkunit5, to prepare input for Hitpro runs. Again, this was done to save labor and eliminate manual errors.

Next, we constructed a shell file, xsm, to copy Hitpro input files from the smoke computer to the patton computer, run Hitpro 20 times, reduce the Hitpro generated gun pointing errors, combine them with stationary errors, and produce hit probabilities.

Finally, we constructed shell files to pull the results back from patton and plot them up on smoke. These plots included hit probability curves and path curves.

2. The Phl program is not documented although AMSAA has begun to do so. While modifying Phl we generated clean, documented code called TAM or Tank Accuracy Model. TAM developed in parallel with this study and is now awaiting approval for publication. Bunn, Fred L., *Tank Accuracy Model*, Army Research Laboratory, Aberdeen Proving Ground MD, 1992, in publication.

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Appendix B. Stationary Target Results

Here are the hit probabilities for the stationary target. In addition, I explain why the cone tail rounds have lower hit probabilities at the lowest muzzle velocities in spite of their lower dispersion.

Hit Probabilities. Table 1 shows the hit probabilities of the four rounds at four target ranges and five muzzle velocities.

TABLE 1. Hit Probabilities

RG (m)	VELOCITY	HEAT	FINNER	4 DEG CONE	15 DEG CONE
1000	1600	.9145	.9295	.9324	.9280
	1800	.9152	.9298	.9330	.9290
	2000	.9155	.9299	.9332	.9290
	2500	.9160	.9300	.9335	.9300
	3000	.9162	.9300	.9336	.9300
2000	1600	.5408	.6040	.6042	.5860
	1800	.5487	.6067	.6111	.5960
	2000	.5533	.6080	.6144	.6010
	2500	.5590	.6092	.6176	.6060
	3000	.5613	.6096	.6189	.6080
3000	1600	.2333	.3360	.3230	.2990
	1800	.2448	.3410	.3366	.3190
	2000	.2515	.3433	.3433	.3290
	2500	.2598	.3455	.3498	.3390
	3000	.2633	.3462	.3522	.3430
4000	1600	.1155	.2046	.1809	.1540
	1800	.1285	.2110	.1990	.1790
	2000	.1366	.2141	.2085	.1940
	2500	.1469	.2171	.2177	.2080
	3000	.1513	.2180	.2210	.2130

The KE hit probabilities for rounds fired at 1600 m/s and at a target at 4000 m range need to be examined further. Although the dispersion for the four degree cone and the 15 degree cone are smaller than for the finner, the hit probabilities are also lower. This is because the cone tailed rounds have higher drag. Therefore, their times of flight are longer and random forces cause larger errors.

Times of Flight. At 4000 meters, the remaining velocities of the rounds are: 1349 m/s, 1036 m/s, and 873 m/s for the finner, 4 deg, and 15 deg cones respectively.

TABLE 2. Times of Flight for 1600 m/s Rounds

RG (m)	FINNER	4 DEG CONE	15 DEG CONE
1000	0.6377	0.6544	0.6636
2000	1.3023	1.3755	1.4187
3000	1.9959	2.1785	2.2952
4000	2.7209	3.0842	3.3371

Error Components at 1.6m/s at 4km Range. As the time of flight increases, the error components shown below increase. Table 3 shows the error components that change between the rounds. The data is for a muzzle velocity of 1600 m/s and a target range of 4000 meters.

TABLE 3. Error Components That Varied

COMPONENT	FINNER	4 DEG CONE	15 DEG CONE
Horiz disp	.26	.247	.221
Horiz cant	.0763	.0901	.1001
Horiz crosswind	.1011	.2675	.3833
Vert disp	.25	.2375	.2125
Muz vel var	.1389	.1819	.2161
Rg est	.0121	.0171	.0213
Rg wind	.0002	.0067	.0118
Air temp	.0095	.0283	.0463
Air density	.0158	.0519	.0854
Vert cant	.0067	.0079	.0087

Appendix C. Moving Target Results

Tables 4 through 12 list the hit probabilities generated for moving targets. Tables 4, 5, 6 present results for the current fire control against three levels of maneuver. Tables 7, 8, 9 present similar results for first order fire controls, and tables 10, 11, 12 present results for second order fire controls.

TABLE 4. Hit Probability on STAGS Target with Current Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	.310	.304	.303	.299
	1800	.332	.328	.327	.322
	2000	.351	.348	.347	.342
	2500	.388	.386	.386	.380
	3000	.415	.414	.414	.408
2000	1600	.138	.132	.130	.114
	1800	.154	.149	.148	.129
	2000	.169	.165	.164	.143
	2500	.200	.197	.198	.172
	3000	.225	.223	.225	.195
3000	1600	.061	.055	.052	.041
	1800	.070	.065	.063	.048
	2000	.079	.074	.073	.055
	2500	.098	.094	.093	.070
	3000	.113	.111	.111	.082
4000	1600	.032	.027	.024	.018
	1800	.038	.033	.031	.022
	2000	.043	.039	.037	.026
	2500	.055	.052	.051	.034
	3000	.066	.063	.062	.042

TABLE 5. Hit Probability on ATMT Target with Current Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	.409	.402	.401	.396
	1800	.437	.432	.431	.424
	2000	.460	.457	.456	.449
	2500	.504	.502	.503	.495
	3000	.537	.536	.537	.529
2000	1600	.188	.180	.178	.157
	1800	.208	.202	.201	.176
	2000	.226	.221	.221	.192
	2500	.263	.260	.261	.228
	3000	.293	.291	.294	.255
3000	1600	.086	.078	.075	.059
	1800	.097	.091	.089	.068
	2000	.108	.103	.101	.076
	2500	.131	.127	.126	.094
	3000	.150	.146	.147	.109
4000	1600	.047	.040	.036	.027
	1800	.054	.049	.046	.033
	2000	.061	.056	.054	.037
	2500	.076	.072	.070	.048
	3000	.088	.085	.084	.057

TABLE 6. Hit Probability on TEMAWS Target with Current Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	.456	.450	.449	.443
	1800	.485	.481	.479	.472
	2000	.508	.505	.504	.497
	2500	.555	.553	.553	.545
	3000	.587	.586	.587	.578
2000	1600	.215	.207	.205	.181
	1800	.236	.230	.229	.201
	2000	.254	.249	.250	.218
	2500	.293	.290	.292	.255
	3000	.323	.321	.325	.283
3000	1600	.102	.094	.091	.071
	1800	.114	.108	.106	.081
	2000	.125	.120	.118	.089
	2500	.148	.145	.145	.108
	3000	.168	.165	.166	.123
4000	1600	.057	.050	.045	.035
	1800	.066	.059	.056	.040
	2000	.073	.068	.065	.045
	2500	.088	.084	.083	.057
	3000	.101	.097	.097	.066

TABLE 7. Hit Probability on STAGS Target with First Order Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	.421	.414	.411	.422
	1800	.454	.448	.446	.454
	2000	.482	.477	.476	.482
	2500	.537	.534	.533	.537
	3000	.576	.574	.575	.576
2000	1600	.170	.160	.155	.170
	1800	.192	.183	.181	.192
	2000	.211	.204	.203	.212
	2500	.253	.248	.249	.253
	3000	.286	.283	.285	.286
3000	1600	.075	.065	.059	.076
	1800	.087	.079	.074	.088
	2000	.099	.091	.088	.099
	2500	.123	.118	.116	.123
	3000	.144	.140	.140	.144
4000	1600	.038	.029	.024	.038
	1800	.045	.037	.033	.045
	2000	.052	.045	.041	.052
	2500	.067	.062	.059	.067
	3000	.080	.076	.075	.080

TABLE 8. Hit Probability on ATMT Target with First Order Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	.543	.534	.533	.525
	1800	.580	.574	.572	.563
	2000	.610	.605	.605	.595
	2500	.667	.664	.665	.654
	3000	.706	.705	.706	.694
2000	1600	.228	.216	.210	.198
	1800	.254	.245	.242	.226
	2000	.278	.270	.269	.251
	2500	.326	.321	.323	.300
	3000	.362	.360	.364	.336
3000	1600	.105	.104	.091	.071
	1800	.119	.119	.108	.086
	2000	.133	.133	.124	.099
	2500	.162	.162	.155	.126
	3000	.185	.184	.181	.147
4000	1600	.055	.055	.043	.030
	1800	.064	.064	.054	.038
	2000	.073	.072	.064	.046
	2500	.091	.091	.084	.063
	3000	.106	.106	.101	.076

TABLE 9. Hit Probability on TEMAWS Target with First Order Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	.585	.577	.575	.567
	1800	.621	.616	.614	.605
	2000	.651	.647	.646	.636
	2500	.706	.704	.705	.693
	3000	.743	.742	.744	.731
2000	1600	.256	.243	.237	.224
	1800	.282	.273	.270	.253
	2000	.306	.299	.298	.277
	2500	.354	.350	.353	.327
	3000	.390	.388	.394	.363
3000	1600	.121	.107	.098	.084
	1800	.137	.125	.119	.100
	2000	.150	.141	.137	.113
	2500	.179	.173	.173	.140
	3000	.202	.198	.200	.160
4000	1600	.067	.053	.044	.037
	1800	.076	.065	.058	.047
	2000	.085	.076	.070	.055
	2500	.103	.097	.094	.073
	3000	.118	.113	.113	.086

TABLE 10. Hit Probability on STAGS Target with Second Order Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	0.474	0.469	0.466	0.461
	1800	0.502	0.497	0.496	0.490
	2000	0.525	0.522	0.521	0.514
	2500	0.570	0.568	0.568	0.560
	3000	0.602	0.601	0.602	0.592
2000	1600	0.211	0.200	0.195	0.184
	1800	0.234	0.226	0.223	0.210
	2000	0.253	0.247	0.246	0.231
	2500	0.292	0.288	0.290	0.272
	3000	0.320	0.318	0.322	0.301
3000	1600	0.093	0.080	0.072	0.061
	1800	0.109	0.098	0.092	0.077
	2000	0.122	0.113	0.109	0.090
	2500	0.149	0.143	0.142	0.117
	3000	0.168	0.165	0.166	0.136
4000	1600	0.044	0.032	0.026	0.021
	1800	0.054	0.044	0.037	0.030
	2000	0.063	0.054	0.049	0.038
	2500	0.082	0.075	0.072	0.056
	3000	0.097	0.092	0.091	0.070

TABLE 11. Hit Probability on ATMT Target with Second Order Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	0.589	0.583	0.581	0.573
	1800	0.621	0.616	0.616	0.606
	2000	0.647	0.643	0.643	0.633
	2500	0.694	0.693	0.694	0.683
	3000	0.726	0.726	0.728	0.716
2000	1600	0.259	0.246	0.240	0.226
	1800	0.288	0.278	0.275	0.256
	2000	0.311	0.304	0.303	0.283
	2500	0.357	0.354	0.357	0.330
	3000	0.390	0.389	0.395	0.363
3000	1600	0.114	0.097	0.088	0.075
	1800	0.133	0.119	0.112	0.093
	2000	0.149	0.138	0.133	0.109
	2500	0.180	0.174	0.173	0.140
	3000	0.203	0.200	0.202	0.162
4000	1600	0.055	0.041	0.033	0.027
	1800	0.067	0.054	0.047	0.037
	2000	0.078	0.067	0.060	0.047
	2500	0.100	0.092	0.089	0.068
	3000	0.117	0.112	0.111	0.083

TABLE 12. Hit Probability on TEMAWS Target with Second Order Fire Control

RG (m)	VELOCITY	FINNER	4 DEG CONE	15 DEG CONE	HEAT
1000	1600	0.618	0.611	0.609	0.601
	1800	0.651	0.646	0.646	0.636
	2000	0.678	0.674	0.675	0.664
	2500	0.726	0.725	0.726	0.714
	3000	0.758	0.758	0.760	0.747
2000	1600	0.272	0.258	0.251	0.235
	1800	0.302	0.291	0.288	0.268
	2000	0.327	0.319	0.318	0.295
	2500	0.375	0.371	0.375	0.346
	3000	0.409	0.408	0.415	0.381
3000	1600	0.121	0.104	0.094	0.080
	1800	0.140	0.126	0.119	0.099
	2000	0.156	0.145	0.141	0.115
	2500	0.189	0.182	0.182	0.147
	3000	0.213	0.210	0.212	0.169
4000	1600	0.061	0.046	0.037	0.031
	1800	0.073	0.060	0.052	0.041
	2000	0.083	0.072	0.066	0.051
	2500	0.106	0.098	0.095	0.072
	3000	0.123	0.118	0.117	0.088

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